Concept of Operations for Air Traffic Management by Managing Uncertainty through Multiple Metering Points

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This paper presents an operational concept for Air Traffic Management, and in particular arrival management, in which aircraft are permitted to operate in a manner consistent with current optimal aircraft operating techniques. The proposed concept allows aircraft to descend in the fuel efficient path managed mode and with arrival time not actively controlled. It will be demonstrated how the associated uncertainty in the time dimension of the trajectory can be managed through the application of multiple metering points strategically chosen along the trajectory. The proposed concept does not make assumptions on aircraft equipage (e.g. time of arrival control), but aims at handling mixed-equipage scenarios that most likely will remain far into the next decade and arguably beyond.

I. Introduction

TRADITIONAL Air Traffic Control (ATC) activities involve the separation and sequencing of airborne aircraft by the controller monitoring the progress of each aircraft and projecting ahead to where they think the aircraft will be in the future. Inaccuracies to this methodology result in large separation standards that limit the number of aircraft that a controller can safely provide service to. Recently, the focus on global warming and CO_2 emissions has provided additional drivers to the call for efficient aircraft operation. These competing issues are compounded by the forecast increases in world air traffic unless action is taken.

In response, the International Civil Aviation Organisation (ICAO) developed the Global Air Traffic Management Operational Concept (GATMOC)[1]. Implementations of GATMOC are represented by NextGen in the United States[2], Single European Sky ATM Research (SESAR) in Europe[3], and the Australian ATM Strategic Plan (AATMSP) in Australia[4; 5]. While there are distinct differences between these programmes, in essence they all introduce a paradigm shift from current airspace-focused ATM to trajectory-focused ATM commonly referred to as Trajectory Based Operations (TBO). Essential to TBO is to increase the level of automation of ATM systems and improve on its interoperability with advanced airborne automation systems, such as the Flight Management System (FMS), to strategically separate trajectories. However prior to the specification of technological requirements, an appropriate concept of operations needs to be determined detailing how to achieve TBO.

A. Arrival Management and Continuous Descent Operations

Arguably arrival management poses the greatest challenge to TBO because of merging traffic streams to the same destination. Often an arrival manager exists at the destination airport setting the landing sequence based on the runway acceptance rate and other operational factors. This sequence is embodied by specific time-based landing slots the individual aircraft in the sequence need to achieve. Currently for most operations around the world, controllers effect the sequence through issuing of tactical instructions within the Terminal Area (TMA). While such methods maintain maximum runway capacity, it does not allow individual aircraft within the landing sequence to optimise their operation given a certain set of constraints and hence conduct an efficient descent.

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Much attention is given around the world to develop a concept of operations that improves on current arrival management by allowing onboard automation to conduct a descent along an efficient profile that better reflects the user intentions and preferences. ICAO refers to such operations as Continuous Descent Operations (CDO)[6]. CDO provide the FMS or pilot with more freedom to manage the descent but brings with it uncertainty to ATC regarding the aircraft's performance and profile. Traditionally, arriving aircraft are controlled through controller initiated step-down descents and sector hand-off agreements to eliminate these elements of uncertainty. To improve on this situation, firstly it needs to be understood how an aircraft plans and executes the descent.

B. Aircraft Descent Guidance Strategies

Geometrically an aircraft navigates along a two dimensional track over the ground which it can achieve with a very high degree of accuracy. The accuracy this track is maintained can even be specified to fractions of a mile[7]. In terms of the remaining dimensions altitude and time, the problem is more complicated and particularly for descent as multiple descent guidance strategies exist.

1. Speed Managed Descent

During a speed managed descent, elevator control is applied to maintain the target Mach or Calibrated Airspeed (CAS) while maintaining idle thrust[8; 9]. A disturbance will be balanced by altitude, i.e. potential energy. If for example the aircraft encounters more headwind than what was predicted by the forecast used in the descent planning phase, the planned descent path is too shallow to be flown at the target speed while maintaining idle thrust. Elevator control is applied and the aircraft is pitched down to maintain the target speed and the aircraft deviates from the planned path.

2. Path Managed Descent

During a path managed descent, elevator control is applied to maintain the planned geometric descent path at idle thrust[8; 9]. A disturbance will be compensated by speed variations, i.e. kinetic energy. If again the aircraft encounters more headwind than forecast, the planned descent path cannot be held at the target speed while maintaining idle thrust. Elevator control is applied and the aircraft is pitched up to maintain the path causing the airspeed to decrease. If required, thrust may be added through throttle control when the airspeed deviates too far below target (auto-throttle or manual). Or similarly, speed brakes deflection (manual) might be required when the speed deviates too far above target.

3. RTA Managed Descent

Some modern FMSs have been equipped with the Required Time of Arrival (RTA) functionality. If a time constraint is specified at a waypoint on the active flight plan, the FMS will attempt to eliminate the difference between the RTA time and the current Estimated Time of Arrival (ETA). On cruise this can be done by either speeding up or slowing down. On descent, a profile change could achieve the same result while maintaining the throttles at idle position.

The RTA descent can be flown as either speed or path managed. In a RTA speed descent the target speed schedule is respected and updated if the current Estimated Time of Arrival (ETA) exceeds the RTA with some threshold value. In a RTA path descent the path is respected where again the speed schedule (upon which the path is based) is updated if the current ETA exceeds the RTA with some threshold value. The speed schedule is based on the Cost Index (CI), so effectively the RTA algorithm varies the CI such that ETA equals RTA.

C. Problem Statement

As the RTA functionality enables an aircraft to achieve a time constraint with high accuracy as proven in several flight trials[10], this mode of operation is considered by SESAR and also NextGen as the backbone of their respective concept of operations to deliver TBO. However, and as will be further argued in this paper, the use of the RTA function has some drawbacks.

Assigning time constraints to points on an aircrafts trajectory results in excess fuel burned, increased engine wear and reduced ride quality as the aircraft continually adjusts its target speed to achieve the assigned time[11]. In addition, and for the descent, the change in target speed schedule comes with change in descent profile[12]. In fact the reduced uncertainty of arrival time at the time-constrained point is transformed into uncertainty of the aircraft's behaviour into that point and beyond that point[13]. As a result two initially separated aircraft both flying to respective appropriately set time-constraints over the same lateral track can infringe separation between them while attempting to achieve the constraint. As a solution time separation between following aircraft could be increased potentially leading to lost longitudinal capacity. This problem has not yet been solved and research is ongoing[14; 15].

Aircraft operation manuals specify the path descent to be most appropriate to meet altitude constraints, ensure (final) approach stability and for fuel economy[16]. However such a descent provides the lowest temporal predictability of the trajectory. Previous work by the authors argued that while temporal predictability is lower compared to other guidance strategies, a path managed descent provides a more predictable descent as a whole due to a consistent descent profile[13]. During a path managed descent, and with three of the four dimensions of the reference trajectory actively controlled, only time remains open. Therefore, is it possible to allow aircraft to perform a path managed descent and manage the uncertainty, then fully contained in the fourth dimension time, strategically using ATC automation rather than tactically with manual controller intervention?

II. Time-Based Sequencing

Prior to answering the question stated at the end of the previous section, some more background information needs to be provided about time-based sequencing. This section will commence to discuss current sequencing procedures in Melbourne, Australia.

A. Arrival Management in Melbourne

Air traffic management techniques for Melbourne manage on average five to six hundred operations per day[17] in a structured terminal area within thirty nautical miles of the airport. Airlines flight-plan the most optimal route to a final route point and then direct to the airport. When the flight is within an hour from Melbourne, controllers issue a standard arrival clearance giving a clear lateral path (Standard Terminal Arrival Route (STAR)) from the final route point to the threshold of the duty runway: vertical constraints ensure separation from departures and jets have a separate path from slower turbo props. Effectively, procedures and airspace are setup for the automation of the aircraft to plan and conduct a continuous descent arrival.

The Eurocat ATC system used in Australia constructs a rudimentary trajectory from the flight plan, performance tables, weather forecast, and position updates which is used by an arrival manager to determine a sequence based on defined parameters such as runway acceptance rates. The sequence is promulgated to enroute controllers in the form of a time ladder showing time to lose by the final route point or Feeder Fix. Controllers ensure the aircraft achieves the specified time at the Feeder Fix with a tolerance of ±60 seconds by implementing a solution based on their own experience and generally occurs after the aircraft has commenced descent. After the Feeder Fix, approach controllers will typically use radar vectoring to fine tune the sequence to maintain runway capacity. Figure 1 shows for a particular arrival how these current sequencing procedures interfere with the preferred descent profile as computed and managed by the onboard automation.

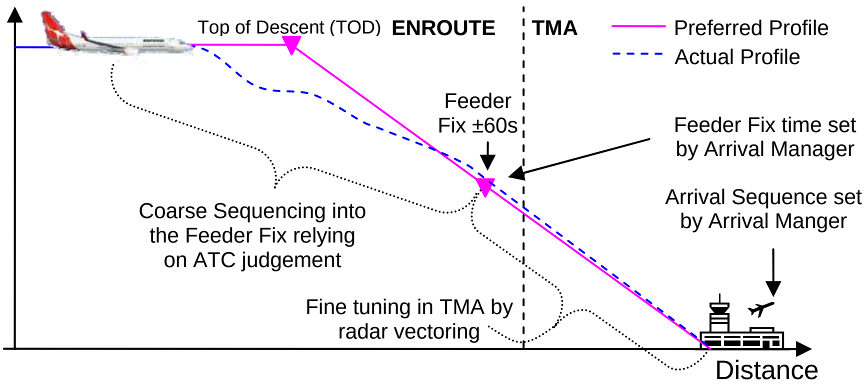

Figure 1. Cross section of current sequencing techniques to Melbourne.

The picture at Figure 2 shows the lateral tracks of 732 arrivals as sequenced by the techniques above. Through the aggregation of the aircraft tracks in the picture the shape of the published STAR path can clearly be seen. The indication from this picture is the terminal route structure is good and most aircraft actually fly the full path to the runway threshold. The reason for aircraft not flying the full path to the threshold would be a timing issue where the aircraft had to be adjusted by vectoring to maintain separation and runway capacity. It can also be inferred from this picture that if the timing

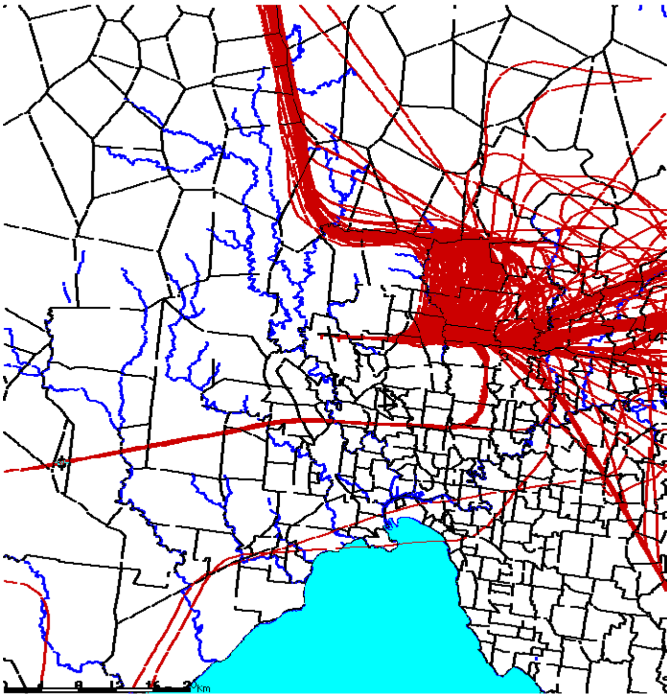

Figure 2. Tracks from 732 aircraft arriving Melbourne runway 27.

was better then less controller intervention would be required or necessary leading to more efficient operations.

The discussion about current arrival management into Melbourne shows that consistent processing of aircraft within the TMA is possible through time-based metering at the TMA entry. Controllers mentally derive speed and route instructions to meet the Feeder Fix time issued by the proprietary arrival manager Maestro. These instructions are mostly based on experience of the individual controller and certain rules of thumb. As these mental techniques only provide sufficient accuracy for a very short prediction horizon, the issuing of the tactical sequence instructions is often left as late as possible and when the aircraft has already commenced descent. Ideally, these speed and route instructions given by the controller should be issued prior to Top of Descent (TOD) such that the FMS can incorporate these additional constraints to optimise its descent while aiming to meet the required time at the Feeder Fix. Therefore, the key role for automation in ATM to play is assist the controller by deriving the right instructions to be issued using models and amounts of supporting data impossible for a human to process. The benefit of specifying speed (and route) instructions to achieve the Feeder Fix time over the use of the RTA function will be discussed later.

B. Speed And Route Advisor (SARA)

Following similar logic, the Speed And Route Advisory (SARA) system has been developed for Amsterdam Schiphol Airport. The objective of SARA is to deliver advisories on speed and/or routing in order to achieve a predetermined time at the Initial Approach Fix (IAF)[18]. An initial accuracy target of ±30 seconds for concept development has been chosen. The SARA speed and route advice is calculated according to local preferences. At first only speed advice is attempted in order to achieve the required IAF time, if speed only does not suffice, additional track miles are added.

Real-time simulations showed that with the use of SARA the variability of arrival times at the IAF was reduced compared to the baseline scenario in which controllers attempted to meet the time through conventional techniques, also controller workload was significantly reduced with use of the SARA tool[19]. Operational trials provided similar results, however because of Amsterdam's complex airspace structure, speed advisories could often only be given after the aircraft has left cruise altitude[20]. This results in some complications to the pilot as the ability to re-plan the descent based on a new speed clearance is limited once descent has been commenced.

C. Enroute Coarse Sequencing

It needs to be noted that speed instructions given around or just after TOD only provides limited sequence resolution to a TMA entry point in the order of 120 seconds. Often much larger delays need to be absorbed by aircraft to fit in their landing slot, thus requiring coarse sequencing to be performed prior to TOD.

This is also considered one of the drawbacks of using the RTA functionality to resolve a delay. As the RTA algorithm changes the CI in order to meet the time constraint, effectively its only degree of freedom to do that is the target speed schedule which makes the situation very similar to issuing a speed instruction by a controller. Again if more delay needs to be absorbed than the RTA function can achieve with CI alteration, controllers will need to revert back to conventional techniques to affect the sequence, at least to shift the aircraft into the envelope of the RTA function.

III. Proposed Concept of Operations

The prime focus of the proposed concept is to allow aircraft to primarily operate in a stable, predictable and constant manner to achieve the business goals for that flight. ATC will be able to issue timely proactive instructions to the aircraft ensuring a conflict free trajectory with minimum affect on aircraft efficiency. Initially it will concentrate on the arrival portion of the flight with objective to allow a continuous descent, and incrementally expand to cover the whole flight including departure.

A. Philosophy

The role of ATC is to separate aircraft which includes arranging them into a landing sequence for the runway threshold. Assuming the controller is not required to navigate the aircraft it will be allowed to operate unconstrained; operated by its flight management system in an automated mode at the maximum efficiency possible to a company determined profile. When the ATC flight data system knows the aircraft has become airborne or departed, it projects ahead and creates a landing time. How accurate this prediction is depends on a number of inputs and sometimes is subject to a large uncertainty. What is known about the flight is that it WILL land at a time in the future however what is uncertain is what the exact time will BE. Uncertainty surrounding an estimate will affect the capacity of a system. Reducing the uncertainty for this is far more difficult. When uncertainties overlap, ATC will probably intervene with a flight to maintain separation.

From a controller perspective and if the aircraft is on its own, it doesn't matter whether the aircraft is earlier or later than the original estimate as no intervention will be necessary. In today's environment should there be another aircraft and the uncertainty of the two aircraft overlap it would cause the controller to consider a last minute path intervention to maintain separation. The future concept of TBO is based on and can only work with accurate trajectory prediction and avoiding last minute tactical intervention.

Controllers use trajectory prediction continually to identify future conflicts and issue timely instructions to sequence and avoid the conflict. A controller's ground system can only predict a trajectory with sufficiently accurate results and minimal uncertainty, when all component parts are known. To simply nominate a time at a waypoint ahead of an aircraft without knowing how the aircraft will operate to achieve that time (RTA function) does not support a concept based around a trajectory synchronised between ground and air. In addition after meeting the time constraint it is not guaranteed that further downwind waypoints will be passed on time[13]. A more logical solution is to have the aircraft controlling to a consistent descent path computed by its FMS; i.e. a known lateral track combined with the vertical component; the path managed descent. As sequencing to an airport is and conceivably will always be managed by the ground, accurate arrival-time estimates must be maintained by any ground system. These times, even though they may be sourced directly from the aircraft still show too large an uncertainty to be used for TBO and maintain an acceptable arrival rate to an airport[21; 22]. For TBO, what is required is a process or system for the ground to have accurate trajectory prediction coupled with a concept of how to practically resolve associated uncertainty.

B. General Concept

To enable a continuous descent to occur for an aircraft, it must be sequenced and facilitated with all other operations. To enable the aircraft automation to operate to the threshold without problems with route discontinuities and manual pilot intervention a couple of assumptions are required:

- A structured terminal area with runway linked STARs enabling the FMS to compute a continuous descent profile within a set of given constraints.
- No adverse weather

Assuming an aircraft can be sequenced to permit it to descend continuously to the threshold; it must be sequenced to a point prior to it commencing descent and thus enabling its descent to be continuous but at a time desired by controllers. Ideally too, for consistency this point should be a defined distance prior to the planned descent point of each aircraft. This clearly poses a problem as the descent point for all aircraft is a result comprised of many inputs: path, level, speed, weather and weight. Therefore the commencement point of descent for an aircraft can either be made known to the ground system by down linking it, flight planning it, or ground estimation. Due to the variable location of TOD as an aircraft encounters winds in flight different to forecast, a better sequencing point is a point defined at a minimal distance prior to TOD. This new sequencing point will be called the Outer Fix and will be nominally 20 nautical miles prior to the top of descent first calculated for an aircrafts trajectory. The Outer Fix is a point created in the ground system only as a sequencing point and is not a flight planned point. A requirement will be for an arrival manager to provide not only a sequence time at the Feeder Fix, but also at each aircraft's Outer Fix. The latter time will be based on a nominal descent speed schedule for that aircraft type.

The outer sector controller will achieve the scheduled Outer Fix time with a tolerance of ±60 seconds through cruise speed and if necessary route adjustment (similar to SARA). In general the further out the action is applied, the greater the delay that can be achieved and still provide a continuous descent arrival. Effectively, the job of the outer sector controller has not changed, but instead of sequencing the aircraft to the Feeder Fix with ±60 seconds the aircraft will be sequenced with the same accuracy to the Outer Fix.

At or prior to reaching the Outer Fix the aircraft will be advised with a descent speed schedule to achieve the scheduled Feeder Fix time. In case the Outer Fix time is passed exactly at the scheduled time, this speed schedule will in theory be the nominal schedule. However as the tolerance for the Outer Fix is ±60 seconds, any deviation from the scheduled time (which propagates to a deviation of the Feeder Fix time and the threshold time), should be resolved by a change in the nominal descent speed schedule. The deviation from the scheduled time at the Outer Fix should therefore be within the tolerance as the ability to absorb delay (or make up time) with just a change in speed schedule for the descent is limited (refer to SARA). It is important the controller is timely alerted if an aircraft will not achieve the Feeder Fix time; this is to enable the amended descent speed to be assigned to the aircraft and entered into the FMS prior to actually commencing descent. Note that while a specific descent speed is assigned, the aircraft is still expected to perform a path managed descent but with the path calculated for the assigned speed. It is expected that the aircraft might not adhere accurately to the target speed. Later in this paper it will be discussed how this problem is resolved.

Complementary to the tolerance for the Outer Fix time is a tightened tolerance for the Feeder Fix reduced to ±30 seconds. This tolerance needs to be achieved by issuing a descent speed schedule, and hence sets an accuracy requirement to the derivation of that speed schedule. Note that this tolerance is similar to SARA and was demonstrated to be achievable for over 80% of the trial flights[20].

Beyond the Feeder Fix normal procedures will be applied to fine tune the sequence to a final tolerance of ±10 seconds at the runway threshold and maintain runway capacity. With the tolerance at the Feeder Fix reduced to ±30 seconds, the need for radar vectoring within the TMA should be reduced and the published STAR in a figure like Figure 2 should become even clearer.

In summary, sequence resolution will be a three phase approach (if necessary):

1. Coarse sequencing or the largest delay occurring before the Outer Fix and descent commencing.
2. Fine sequencing by assigning a specific descent speed so the aircraft automation adjusts its descent point and path to cross the Feeder Fix at the desired time.
3. Precise sequencing using radar vectoring similar to techniques of today but expected to be used far less often due to the tighter sequencing to the Feeder Fix.

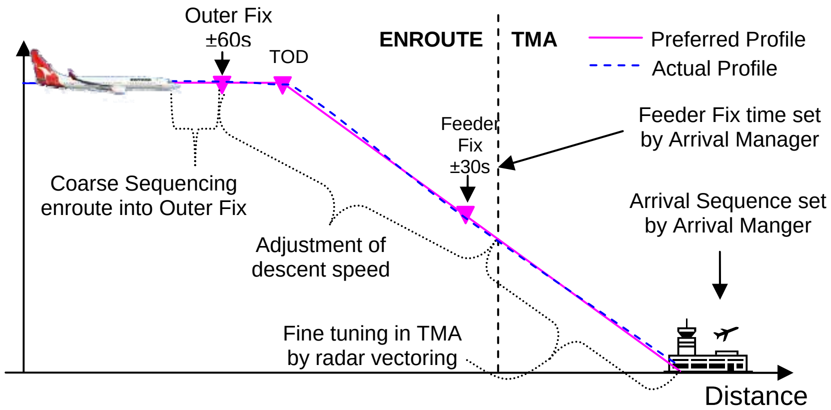

Figure 3. Proposed sequencing concept using Outer Fix.

The diagram in Figure 3 portrays how this would be achieved by shifting the coarse sequencing prior to descent. If the coarse target has been achieved then the ±30 seconds time target for the Feeder fix permits the aircraft to descend without lateral adjustment and any variation to the Feeder Fix can be corrected by assigning a descent speed prior to the aircraft commencing its descent. A descent speed assigned prior to commencing descent will cause the aircraft automation to recalculate the descent path for the changed speed resulting in an amended time at the Feeder Fix. The aircraft will descend continuously to the runway at the amended speed controlled by the cockpit automation and unintentionally achieve the controller desired time at the Feeder Fix (within the tolerance). For a controller to fine tune the sequence further, the option to vector and position the arriving aircraft appropriately still remains. It is expected unless necessary this practice will be discouraged.

C. Detailed Concept

The proposed concept is about understanding and managing the uncertainty of an aircraft flight path such that many trajectories can be operated in unison and harmony. In Figure 3, for each location there is a defined time that is recognised as having an acceptable tolerance that must be achieved for the system to work. This concept suggests methods to achieve the times within the applicable tolerances while allowing the aircraft to operate consistently and as efficiently as possible.

1. Process

- A landing sequence will be determined at the arrival airport considering all associated requirements e.g. demand, acceptance rate etc.
- Times in a sequence will be defined in seconds and a “slot” will be maintained for scheduled aircraft until any delay precludes them achieving the reserved time.
- The arriving aircraft trajectory will be transposed to meet the landing time defined by the sequence giving adjusted times for the Feeder and Outer Fixes.
- Outer Fix - a ground generated point specific to a particular flight 20NM prior to the TOD of that aircraft. As TOD likely differs between aircraft, it will be different for all aircraft.
- Feeder Fix – effectively entry point for the terminal area.
- Descent to be on the lateral track, continuous from cruise level to achieve the times for the metering points with the following increasing tolerance for accuracy. Outer Fix time ±60 seconds, Feeder Fix ±30 seconds, Threshold ±10 seconds.
- Coarse sequencing to the Outer Fix will be via cruise speed or route adjustment.
- Fine sequencing to the Feeder Fix will be via assigned speed for descent.
- Precise sequencing to the runway will be via radar vectoring as required.
- ATC, supported by ground automation will take proactive steps to facilitate aircraft operating to the airline defined profiles.
- All aircraft will be processed the same way although less equipped aircraft may require more manual intervention.

2. Supporting Technology

ATC will be supported by a ground-based Trajectory Predictor (TP) with sufficient accuracy including the following requirements:

- The TP will continually monitor aircraft conformance to the sequenced trajectory.
- The TP will alert the controller if the arrival time estimates are outside the tolerance for a point.
- The TP will calculate solutions to efficiently resolve for the aircraft, a method to regain the sequenced trajectory.
- The TP will use input acquired from ground and airborne sources (data-link). The predicted trajectory is based on synchronised aircraft *intent* between FMS and ATC, but the predicted *trajectory* is not necessary equal to that of the FMS which will be detailed later in this paper.

These accuracy requirements will be discussed later.

3. Staged Sequencing through Multiple Metering Points

Stage 1: Coarse sequencing identified to be required well prior to top of descent.

- The TP identifies the aircraft will arrive at the Outer Fix outside of the buffers for the assigned time i.e. greater than ±60 seconds different.
- The TP suggests a resolution to ATC to amend the current trajectory to adjust the arrival time to the Outer Fix sequence time.
- Cruise trajectory amendment could occur a second time.
- If the sequence time achieved then aircraft will descend at desired/nominal speed schedule.

Stage 2: Fine sequencing to occur during descent but identified prior to descent commencing.

- The TP identifies the aircraft will arrive at the Feeder Fix outside of the buffers for the assigned time i.e. greater than ±30 seconds different.
- Prior to commencing descent the TP suggests to ATC an amended descent speed to adjust arrival time to Feeder Fix sequence time. The expectation is for the aircraft to conduct a path managed descent with the path based on the advised descent speed.
- If the Feeder Fix sequence time is achieved then aircraft will continue at assigned speed.
- ATC continues to have option of radar vectoring if necessary.

Stage 3: Precise sequencing to occur within TMA, but identified prior to the aircraft passing the Feeder Fix.

- Aircraft not touched unless necessary.
- The TP identifies the aircraft will arrive at the threshold outside of the buffers for the assigned time i.e. greater than ±10 seconds different.
- ATC uses radar vectoring if necessary to fine tune sequence (but only in a limited manner as ensured by meeting previous sequence tolerances).

IV. Clarification and Example

1. Uncertainty

To aid the reader's understanding of uncertainty related to aircraft estimates consider the following: Figure 4 and similar graphs in this document compare aircraft location in distance from the destination to a time axis. In Figure 4 an aircraft is at a point prior to descent and from its current position, path and speed a TP calculates an ETA for TOD, Feeder Fix and the runway threshold. Effectively, the dashed line provides a reference to the ETA at a particular position ahead of the aircraft continuous with distance. These estimates contain some uncertainty as the models for aircraft intent, aircraft performance model and forecast weather are not perfect. The uncertainty can be statistically quantified through historical performance of the respective TP[21; 23]. Logically, the further out an estimate is made, the larger the related uncertainty associated with that estimate. The blue shaded area provides an indication of the uncertainty, quantified as the historical 95% containment area, as it grows with prediction horizon (distance away from current position). These models are similar to those developed by EUROCAE Working Group 85 (WG85) for ETA uncertainty in both open loop and closed loop (RTA) operations based on the sources of this uncertainty [24; 25].

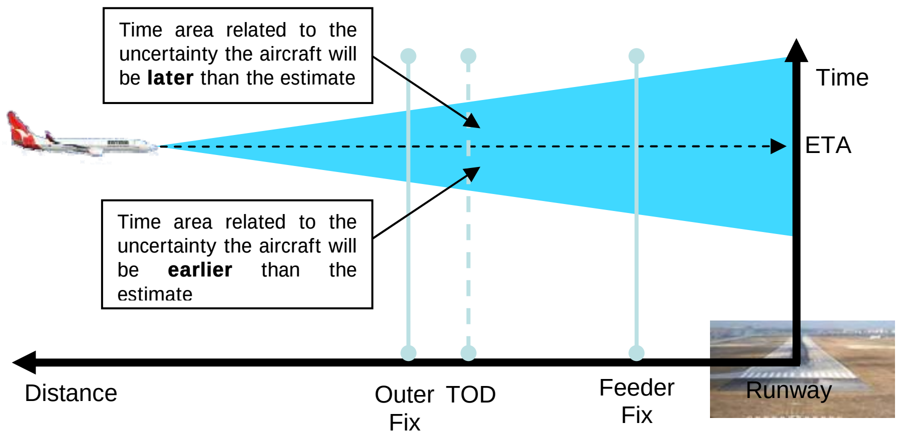

Figure 4. Proposed sequencing concept using Outer Fix.

For the trajectory based operations of the future it is logical to state that the more accurate the prediction is and therefore the smaller the uncertainty, the better operations can be planned. However there will always be an associated value of uncertainty and this uncertainty will need to be managed.

2. Example in Practice

Suppose that the aircraft in Figure 4 is assigned with a scheduled time of arrival (STA) at the runway threshold by the arrival manager (see Figure 5). From this STA, subsequently STAs for the Feeder Fix and Outer Fix can be derived. Similar to the line indicating the ETA continuous with distance, a line can be added to indicate the STA continuous with distance; this continuous STA coincides at the Outer Fix and Feeder Fix with the respective discrete STA values. Therefore in Figure 5, the STA lines provide an indication of where the aircraft should be in order to be 'on schedule'. In the example the ETA line is above the STA line and hence currently the aircraft is late. Previously the different tolerances for the Outer Fix, Feeder Fix and runway threshold were presented and are these are also indicated in Figure 5.

The aircraft shown in Figure 5 is late to its assigned sequence time and the runway estimate uncertainty shows the aircraft will most likely not achieve its sequence time at the runway without intervention or issuing a new sequence time.

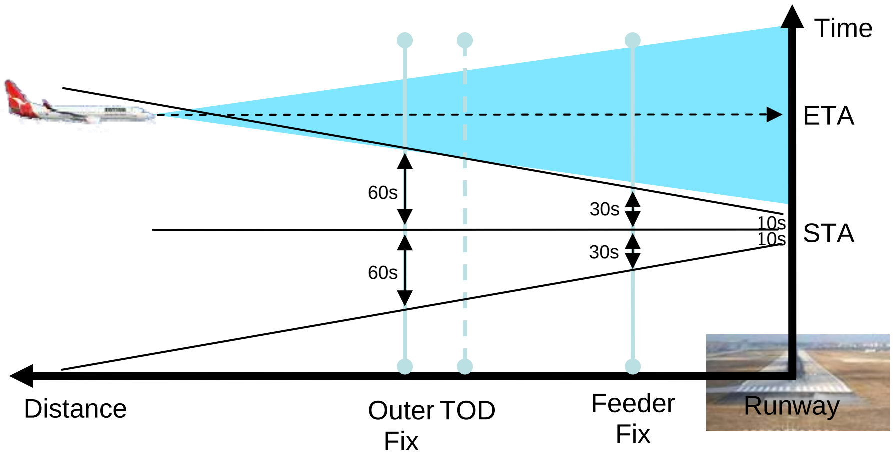

Figure 5. First sequence instruction into Outer Fix affected.

In the proposed concept, the TP computes a cruise speed amendment, and if necessary a route amendment, to affect the sequence resolution into the outer fix. These sequencing instructions can be issued in a proactive manner via data-link if the aircraft is sufficiently equipped. Data-link capability is particularly useful for such application as it both provides a means to accurately transfer the instruction to the cockpit and then to monitor conformance. With speed (and route) advisory, the aircraft's ETA line now coincides with the RTA line as indicated in Figure 6. However because it is so far out – prior to descent – the prediction uncertainty delta of the estimate at the runway and Feeder Fix is larger than the target time window. However in terms of the Outer Fix the uncertainty is entirely contained within the tolerance because of the first sequence instruction. Therefore the aircraft is permitted to proceed without further intervention to at least the Outer Fix, and with the expectation of a continuous descent thereafter. But as the uncertainty at the Feeder Fix is larger than the tolerance, the descent speed for that continuous descent might have to be adjusted.

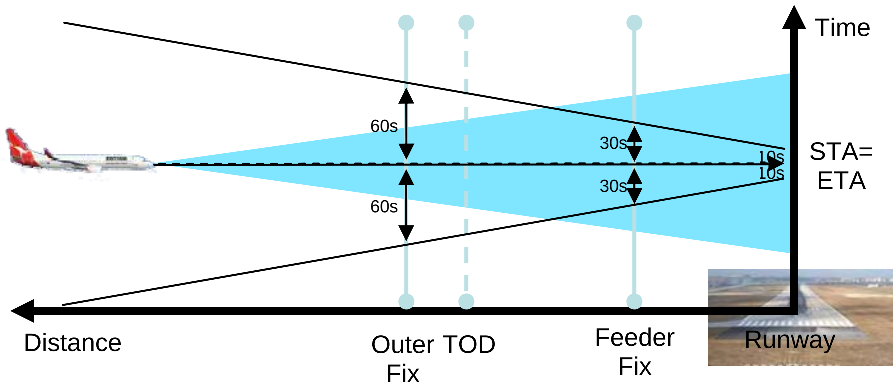

Figure 6. First sequence instruction into Outer Fix affected.

The situation would need to be monitored by the controller assisted by ATC automation until the aircraft comes close enough to a target window (e.g. Feeder Fix) such that the uncertainty for its respective estimate is entirely contained within the tolerance. Practically what it means is that if the uncertainty is not fully contained within the target window, there is a probability larger than 5% that any sequence instruction derived by the TP is not effective. With effective it is meant that the aircraft is

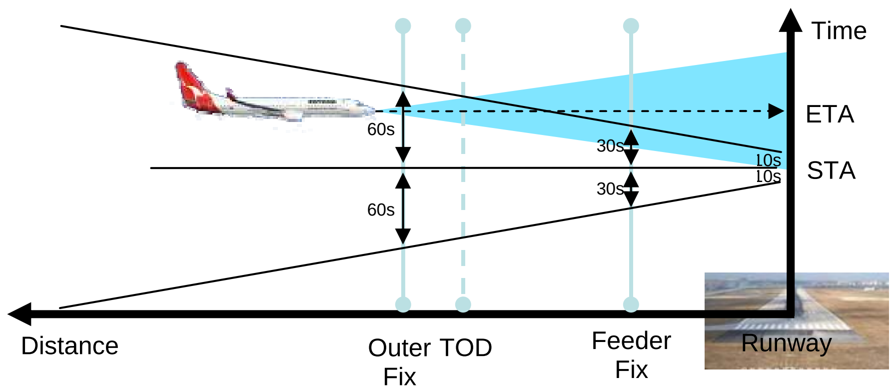

Figure 7. Aircraft late, but within time window at Outer Fix but not at Feeder Fix.

making the target window with the derived instruction.

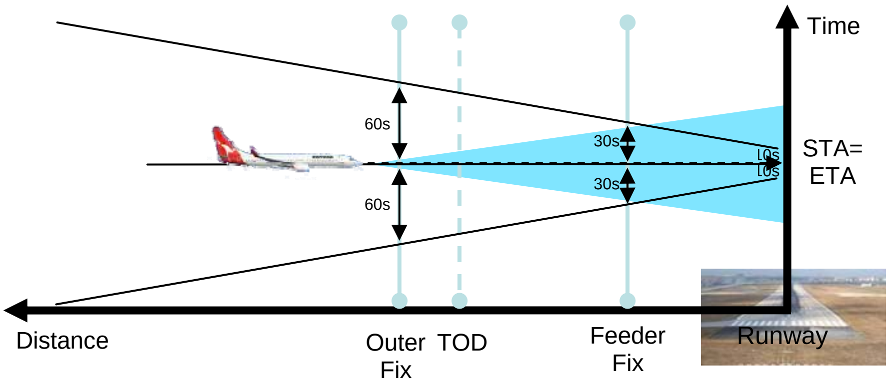

Figure 8. Second sequence instruction into Feeder Fix affected.

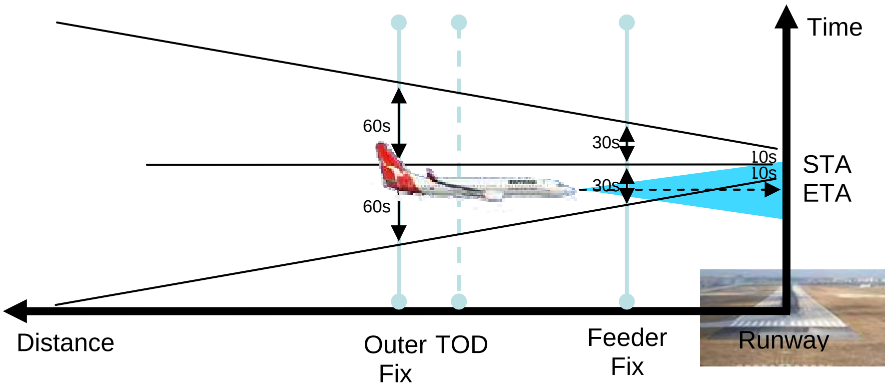

Figure 9. Aircraft on descent in tolerance but threshold ETA early.

Now consider Figure 7, the aircraft has progressed and the ETA has drifted away from the STA as there is no closed-loop control in the time dimension. Still the aircraft will achieve the target window at the Outer Fix within acceptable buffer but not the Feeder Fix. Therefore a descent speed higher than nominal will be derived by the TP and delivered to the aircraft to shift the ETA at the Feeder Fix to the STA (Figure 8). The applied speed should be maintained until mandated speed changes e.g. 250 knots IAS below ten thousand feet. This intervention issued before TOD will enable an efficient and continuous descent at a speed that puts the aircraft back into the defined sequence position. Note that for the speed instruction to be effective, the uncertainty of the ETA as derived by the TP and used to determine the speed adjustment, needs to be less than the Feeder Fix tolerance of ±30 seconds.

The aircraft in Figure 9 will achieve the Feeder Fix within the target window but will be outside the target window for the threshold (early). Consequently the aircraft will require radar vectoring to achieve the time at the runway. This is very similar to today however it is expected to be required for far less flights than today, and to a smaller extent as the Feeder Fix is passed with higher accuracy than today. This radar vectoring should occur between passing of the Feeder Fix and the start of an instrument approach or RNP arrival procedure.

3. Sequence Resolution Space

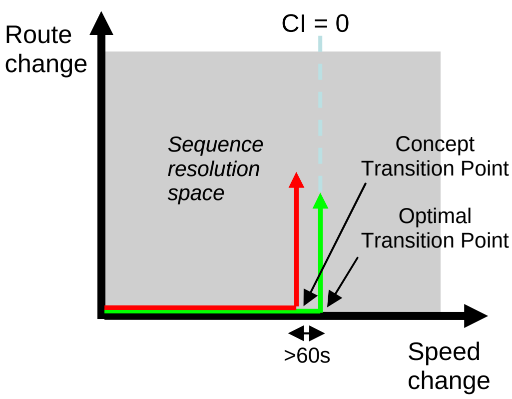

Figure 10. Sequence Resolution Space.

It was previously mentioned that the coarse sequencing into the Outer Fix will be effected firstly through cruise Mach number change and a route amendment will be made if speed adjustment alone is not sufficient. In theory, and assuming a delay needs to be absorbed in an efficient manner, this transition point coincides with the cruise speed at which the Cost Index (CI) is zero (minimum fuel speed) (Figure 10). Inclusion of the descent makes the problem more complex as also descent speed schedule needs to be taken into consideration[26]. In terms of the proposed operational concept it is undesirable to sequence an aircraft into the Outer Fix using the full capability of speed adjustment. If for example an aircraft has been instructed to fly at zero CI and due to normal time drift the Outer Fix is passed early, there is no possibility remaining to resolve this drift with a speed change into the Feeder Fix, i.e. the degree of freedom of a speed change in the sequence resolution space has been exhausted (in one direction). ATC then may have to revert to conventional procedures to affect the sequence which most likely will impact on the efficiency the descent is executed. Therefore, the transition point after which a route amendment should be made to affect the sequence into the Outer Fix, should leave sufficient buffer within the speed change degree of freedom to allow for the ±60 seconds tolerance at the Outer Fix to be resolved plus a TP uncertainty buffer.

Study is required to determine the most efficient methodology to lose time into the Feeder Fix in the context of the proposed operational concept.

4. The Need for Accurate Ground-Based Trajectory Prediction

Until now one major assumption has been made about the proposed operational concept: a sufficiently accurate TP is available to derive instructions to deliver aircraft to the different metering points within the target window. In fact, the minimum required performance of the TP is set by the target windows of the metering points and the sequence horizon.

It has been demonstrated that the uncertainty of an estimate derived from the TP (and therefore also of a sequence instruction derived from the TP), needs to be smaller than the target window in order for an instruction to be effective. The combination of the accuracy of the TP and the target window therefore directly sets the maximum horizon. Any instruction derived from the TP beyond this horizon is less than 95% effective. This horizon can be easily determined from the size of the target window and the slope of the uncertainty cone as the latter is a quantification of the TP performance. Thus in generic terms, the slope of the *uncertainty* cone related to the performance of the TP needs to be smaller than the slope of the *target* cone, and thus setting the accuracy requirement for a TP supporting the proposed concept of operations.

The cruise phase of flight generally involves a stable wind and level flight making the prediction of times from the calculated groundspeed relatively simple. The descent phase of flight occurs through a significant band of winds and varied aircraft performance driven by the airline priorities on the day and makes this a much more difficult problem. In relation to the concept, the critical requirement for the TP would be to derive speed instructions that delivers an aircraft to ±30 seconds accuracy at the Feeder Fix. These speed instructions need to be derived when the aircraft is approaching the Outer Fix but not later than crossing the Outer Fix (requirement for horizon). Therefore predictions of the ETA at the Feeder Fix need to have at least this accuracy and preferably better.

In previous research work the authors investigated the accuracy of the TP currently operational in Australia’s EUROCAT ATC system and compared it to predictions made by the aircraft’s FMS and the experimental Airservices TP (ATP). For a large number of Boeing 737-800 (B738) flights that conducted a non-intervened continuous descent predictions made by the three systems for the ETA at the

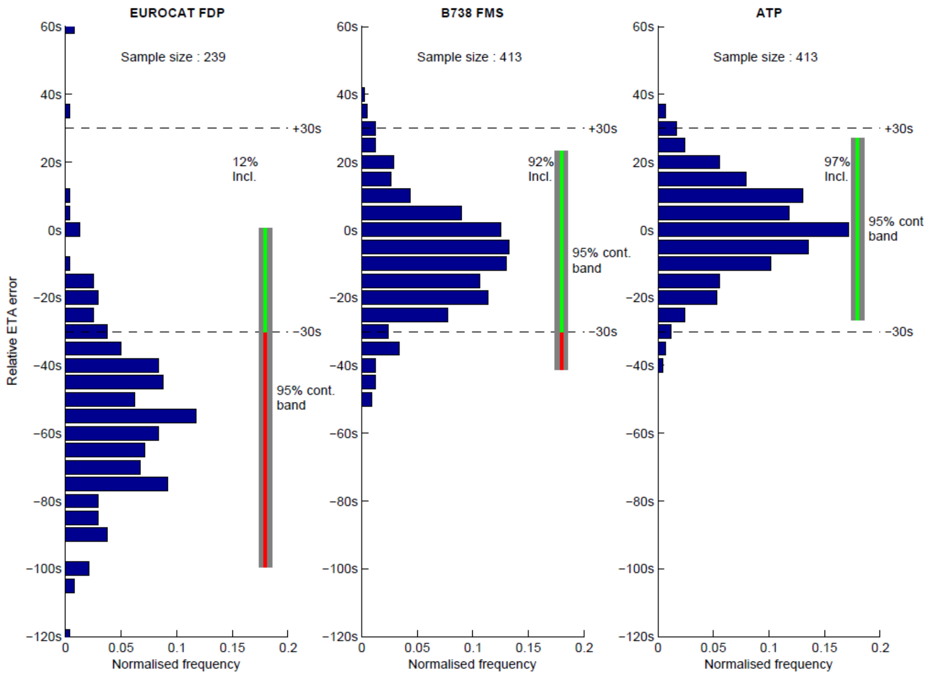

Figure 11. TP performance comparison.

Feeder Fix were compared. In each case the prediction was made when the aircraft was at the position of the proposed Outer Fix. The results are given in Figure 11.

It is clear that with the FDP trajectory estimates of the current ATM system this operational concept cannot be considered as only 12% of the sampled flights meet the accuracy requirement. Other operational concepts around the world promote the use of estimates down-linked from the aircraft's FMS. As with FDP estimates, the accuracy requirement of 95% is only met for 92% with this aircraft and FMS combination. Previous research on other aircraft and FMS combinations has indicated similar or lower performance[21; 22] leading the authors to believe that accurate trajectory prediction can only be achieved when information available by the FMS in the air and by ATC on the ground is appropriately combined[27].

The experimental ground-based Airservices TP developed by these authors does meet the accuracy requirement with 97% within target. ATP appropriately combines data extracted from the FMS via Future Air Navigation Systems (FANS) and data available on the ground, and takes into account the active guidance strategy (path managed descent)[27]. In essence ATP is able to predict the deviations from the target speed as a result of holding the path at idle thrust. Integration of these speed changes results in an improved ETA at the Feeder Fix. It was previously mentioned that in the proposed concept an updated speed schedule is expected to be flown path-managed to maintain a consistent and predictable profile. Supported by the latter prediction algorithms the speed deviations associated with the path managed descent, and hence the reduced temporal predictability, do not pose a problem.

While in all these cases aircraft down-linked information was available, current research work is being performed to configure ATP for non data-link equipped aircraft. It is expected that some degradation in accuracy will occur, however if critical parameters to the prediction process can be communicated to ATC via voice, and with the application is system learning techniques, this degradation should be minimal. In essence however, equipped and non-equipped aircraft will be processed the same.

5. Energy Management

Flying an aircraft efficiently is all about effective energy management. The reference trajectory computed by the FMS can be seen as the realisation of the acquiring (climb) and dissipation (descent) of the total energy (kinetic and potential) possessed by the aircraft. Therefore, if any inaccuracies exist in computing the reference trajectory, this trajectory will not accurately reflect the total energy possessed by the aircraft at different stages in the flight. On descent, it is this error in predicted total energy that subsequently needs to be managed with an appropriate guidance strategy. The energy error is therefore closely related to the uncertainty in the descent trajectory executed by the aircraft. The dimension(s) in which this uncertainty is (are) contained is a direct result of the selected descent guidance strategy.

Effectively, the guidance strategy balances the error in predicted total energy using either potential or kinetic energy. When balancing with potential energy, the reference altitude profile will be departed (e.g. speed managed). When balancing with kinetic energy, speed (and time) will be affected (path managed). Note that departing the reference altitude profile will also indirectly affect time[13]. Energy can also be added through the application of thrust or dissipated through the application of speed brakes. Either way it will be the guidance strategy commanding these active energy management actions.

In summary, the deviations (in all dimensions) from the reference trajectory can be seen as a measure of the error in the total energy as predicted by the FMS and thus forms a measure of uncertainty in the predicted trajectory.

When a TP computes a descent trajectory, effectively it implicitly determines the total energy that will be dissipated on descent. Logically, the better the total TP model (forecast conditions, intent and aircraft performance), the better the estimate of the dissipated energy and the less the uncertainty

Consider Figure 12, the left column represents the *actual* energy that is dissipated over the FMS computed descent path, the middle column the value implicitly determined by the FMS, and the right column the value found by ATP after simulating the execution of the descent. The FMS predicted energy for descent is reflected in the geometry of the descent profile it computed. ATP takes the path from the FANS trajectory data, and hence follows this same descent profile. However, the ground-

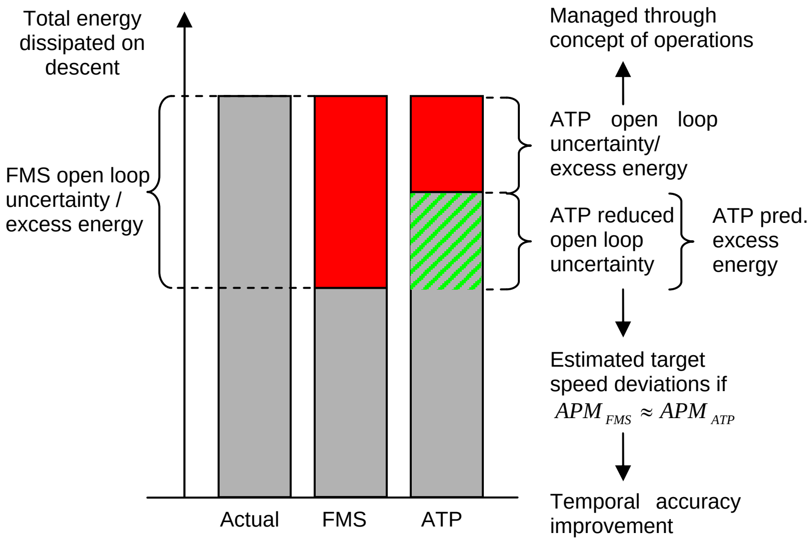

Figure 12. TP performance comparison.

based forecast model used by ATP is of much higher resolution and precision than the one held by the FMS. Therefore, ATP is able to estimate some of the excess energy on as discussed in much detail in Ref [27]. The remaining excess energy, which is a measure of the remaining uncertainty in the system, will need to be managed through the concept of operations.

When applied to the RTA functionality, it is effectively the energy error represented by the red top in the FMS bar that needs to be accounted for by additional fuel burn (or dissipated through speed brake deployment) at some stage prior to landing as discussed into detail in Ref [13]. If a ground based TP is able to predict the fourth dimension of the trajectory of an aircraft descending in path managed mode better than the FMS, and the remaining uncertainty (i.e. energy error) can be managed through a concept of operations as proposed in this paper, it then seems unnecessary for the aircraft to compensate for the energy error and thus consume additional fuel.

V. Comparison with Other Concepts and Concluding Remarks

Both SESAR and NextGen propose that aircraft will be assigned times at waypoints which they must achieve with a high accuracy (RTA functionality). In order to do this, the free variable or dimension in their operation which they will use to control to the assigned time is their speed. Any unexpected speed change by an aircraft will cause increased workload to a controller as the impact of such a change is assessed. Different FMSs can have different RTA algorithms, and even with the same algorithm, depending on the forecast winds entered in the FMS and other specific settings, different speed schedules can be computed and also updated differently. As previously mentioned two initially separated aircraft both flying to respective appropriately set time-constraints over the same lateral track can infringe separation between them while attempting to achieve the constraint. A concept relying on airborne equipment to meet time constraints is therefore not “set and forget” but requires continuous monitoring by controllers.

Instead, this paper proposes a concept in which aircraft are permitted and expected to operate consistently without unexpected changes to their operation which induces additional uncertainty. The concept envisions aircraft to conduct a continuous descent in path managed mode. In path managed mode the aircraft can conduct a continuous descent along a consistent descent profile with the uncertainty contained in the temporal dimension of the trajectory. ATC is subsequently supported by accurate ground-based trajectory prediction to manage this temporal uncertainty though metering at strategically chosen points along the aircraft’s trajectory. Instead of being ATC-focused, the concept aims to focus on the consistent and efficient operation of aircraft.

The concept promotes the use of data link to share trajectory related information between crew/FMS and ATC. The use of data link allows strategic clearances to be issued expeditiously and efficiently rather than late tactical interventions issued by voice although that always remains an option if required. ATC procedures in this concept do not widely deviate from today’s procedures and therefore it is envisioned the concept can successfully deal with mixed-equipage scenarios.

This concept is attempting to facilitate aircraft operating efficiently and predictably. It is the opinion of the authors, an operational concept based on the consistent processing of all aircraft has the highest likelihood of being successfully implemented prior to the end of this decade.

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